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| (54) Title: A METHOD OF DESIGNING FPGAS FOR DYNAMICALLY RECONFIGURABLE COMPUTING <div data-bbox="263 1125 1310 1549" data-label="Diagram"> <pre> graph LR 201[User Java Code] --> 203((JAVA Compiler)) 202[MDRC Libraries] --> 203 203 --> 204[Executable Code] 204 <--> 106[FPGA] </pre> </div> | | |
| (57) Abstract <p>A method of designing FPGAs for reconfigurable computing comprises a software environment for reconfigurable coprocessor applications. This environment comprises a standard high level language compiler (i.e. Java) and a set of libraries. The FPGA is configured directly from a host processor, configuration, reconfiguration and host run-time operation being supported in a single piece of code. Design compile times on the order of seconds and built-in support for parameterized cells are significant features of the inventive method.</p> | | |

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A METHOD OF DESIGNING FPGAS FOR
DYNAMICALLY RECONFIGURABLE COMPUTING

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BACKGROUND OF THE INVENTION

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Field of the Invention

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Description of the Background Art

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In recent years, there has been an increasing interest in reconfigurable logic based processing. These systems use dynamically reconfigurable logic, such as FPGAs that can be reconfigured while in use, to implement algorithms directly in hardware, thus increasing performance.

By one count, at least 50 different hardware platforms (e.g., computers) have been built to investigate this novel approach to computation. Unfortunately, software has lagged behind hardware in this area. Most systems today employ traditional circuit design techniques, then interface these circuits to a host computer using standard programming languages.

Work done in high-level language support for reconfigurable logic based computing currently falls into two major approaches. The first approach is to use a traditional programming language in place of a hardware description language. This approach still requires software support on the host processor. The second major approach is compilation of standard programming languages to reconfigurable logic coprocessors. These approaches typically attempt to detect computationally intensive portions of code and map them to the coprocessor. These compilation tools, however, are usually tied to traditional placement and routing back-ends and have relatively slow compilation times. They also provide little or no run-time

1 support for dynamic reconfiguration.

2 In general, today's tools are based on static circuit
3 design tools originally developed for use in circuit board
4 and integrated circuit design. The full potential of
5 dynamic logic is not supported by such static design tools.

6
7 SUMMARY OF THE INVENTION

8 The method of design for reconfigurable computing
9 (MDRC) of the invention represents a novel approach to
10 hardware/software co-design for reconfigurable logic based
11 coprocessors. A system and method are provided for
12 configuring an FPGA directly from a host processor. It is
13 not necessary to store the configuration data in a file,
14 although it can be so stored if desired. Therefore, this
15 method is particularly suited for use with FPGAs such as
16 reconfigurable coprocessors, which are often reconfigured
17 "on the fly", i.e., without repowering the FPGA and
18 sometimes while reconfiguring only a portion of the FPGA. A
19 description of the desired functionality for the FPGA is
20 entered using the MDRC libraries and a standard high level
21 language such as Java™ (Java is a trademark of Sun
22 Microsystems, Inc.). Configuration, reconfiguration and
23 host interface software for reconfigurable coprocessors is
24 supported in a single piece of code.

25 Since MDRC does not make use of the traditional
26 placement and routing approach to circuit synthesis,
27 compilation times are significantly shorter than with prior
28 art methods, being on the order of seconds. This high-speed
29 compilation provides a development environment which closely
30 resembles those used for modern software development.

31 The MDRC provides a simple alternative to traditional
32 Computer Aided Design (CAD) tool based design. In the
33 preferred embodiment, Java libraries are used to program an
34 FPGA device. This method has the following benefits:

35 Very fast compilation times. Because standard
36 programming language compilers are used by this approach,
37 compilation is as fast as the host native compiler. With

1 current Java compilers such as Microsoft's J++ 1.1 compiler
2 compiling over 10,000 lines of code per second, compiling
3 circuits built using MDRC will take on the order of a second
4 to complete. This is in contrast to the hours of turnaround
5 time in existing CAD tools.

6 Run time parameterization of circuits. Perhaps the
7 most interesting feature of MDRC is its ability to do run-
8 time parameterization of circuits. For instance, a constant
9 adder, using a constant value known only at run-time, can be
10 configured by MDRC during execution. The size of a given
11 component may also be specified dynamically. A 5-bit adder
12 or a 9-bit counter, for instance, can be configured at run-
13 time. This feature has uses in areas such as adaptive
14 filtering.

15 Object Oriented Hardware Design. Because Java is an
16 object oriented language (i.e., a structured language in
17 which elements are described in terms of objects and the
18 connections between these objects), hardware designed in
19 this language can make use of object-oriented support.
20 Libraries constructed with MDRC may be packaged as objects
21 and manipulated and reused like any standard software
22 component.

23 Support for dynamic reconfiguration. The ability to
24 dynamically configure a circuit automatically brings with it
25 the ability to do dynamic reconfiguration. Uses for this
26 capability are beginning to appear. For example, a portion
27 of a dynamically reconfigurable FPGA could be configured as
28 a multiplier that multiplies an input value by a constant,
29 the constant being a scaling factor in a signal processing
30 application. Using dynamic reconfiguration, this scaling
31 factor could be changed without interrupting the function of
32 other portions of the configured FPGA.

33 Standard software development environment. Using a
34 standard programming language (in this case, Java) permits
35 standard software environments to be used by circuit
36 developers. In other words, widely available, off-the-shelf
37 compilers such as Microsoft's J++ 1.1 compiler could be used

1 to develop circuits to be implemented in an FPGA. This
2 capability has two immediate advantages. First, the user
3 can continue to use whichever tool he or she is already
4 familiar with. Secondly, and perhaps most importantly, FPGA
5 design becomes a software development effort open to
6 programmers. This capability could greatly expand the
7 existing base of FPGA users.

8 Simplified host interfacing. MDRC requires a host
9 processor to be available for executing the Java code and
10 supplying configuration data to the FPGA. This
11 processor/FPGA combination is a powerful coprocessing
12 environment currently being investigated by researchers.
13 One barrier to use of these systems is the need to interface
14 the FPGA hardware design with the host software design.
15 MDRC merges the software and hardware design activities into
16 a single activity, eliminating these interfacing issues.

17 Flexibility. Because MDRC comprises a library used by
18 a standard programming language, it may be extended, even by
19 users. This capability provides a level of flexibility
20 unavailable in a static design tool. Users are free to
21 provide new libraries and library elements, or even
22 accessories such as custom graphical user interfaces.

23 Standard device interface. One way to think of MDRC is
24 not so much as a tool in itself, but as a standard interface
25 to the FPGA device. This interface may be used for FPGA
26 configuration, or it may be used to build other tools. MDRC
27 may even be used as the basis for traditional CAD software
28 such as placement and routing tools. Another way to think
29 of MDRC is as the "assembly language" of the FPGA.

30 Guaranteed "safe" circuits. MDRC provides an
31 abstraction (a software construct that provides a
32 representation, often simplified, of the hardware) which
33 makes it impossible to produce circuits with contention
34 problems. This makes it impossible when using MDRC to
35 accidentally damage or destroy the device due to a bad
36 configuration. Such protection is highly desirable in a
37 dynamic programming environment like MDRC, where a

1 programming error could otherwise result in permanently
2 damaged hardware. (An incorrectly configured FPGA may
3 inadvertently short power and ground together, destroying
4 the device.) A side effect of this feature is that the MDRC
5 may be used as an implementation vehicle for the emerging
6 field of genetic algorithms.

7
8 BRIEF DESCRIPTION OF THE DRAWINGS

9 The aforementioned objects and advantages of the
10 present invention, as well as additional objects and
11 advantages thereof, will be more fully understood
12 hereinafter as a result of a detailed description of a
13 preferred embodiment when taken in conjunction with the
14 following drawings.

15 Figure 1 is a block diagram illustrating the prior art
16 design flow for design of a circuit implemented in an FPGA
17 using a reconfigurable logic coprocessor.

18 Figure 2 is a block diagram illustrating the design
19 flow in the present invention.

20 Figure 3 is a diagram of a level 1 logic cell
21 abstraction of the present invention.

22 Figure 3A is a diagram of an XC6200 logic cell
23 represented by the abstraction of Figure 3.

24 Figure 4 is a diagram of a multi-bit counter according
25 to one embodiment of the invention.

26 Figure 5 is an element definition code listing for the
27 basic elements of the embodiment of Figure 4.

28 Figure 6A is a diagram of a toggle flip-flop cell of
29 the embodiment of Figure 4.

30 Figure 6B is a diagram of a carry logic cell of the
31 embodiment of Figure 4.

32 Figure 7 is a configuration code listing for the
33 counter of Figure 4.

34 Figure 8A is a run time code for the counter of Figure
35 4.

36 Figure 8B is an execution trace for the counter of
37 Figure 4.

1 DETAILED DESCRIPTION OF THE DRAWINGS

2 Design of a circuit implemented in an FPGA using a
3 reconfigurable logic coprocessor currently requires a
4 combination of two distinct design paths, as shown in prior
5 art Figure 1. The first and perhaps most significant
6 portion of the effort involves circuit design using
7 traditional CAD tools. The design path for these CAD tools
8 typically comprises entering a design 101 using a schematic
9 editor or hardware description language (HDL), using a
10 netlister 102 to generate a netlist 103 for the design,
11 importing this netlist into an FPGA placement and routing
12 tool 104, which finally generates a bitstream file 105 of
13 configuration data which is used to configure FPGA 106.

14 Once the configuration data has been produced, the next
15 task is to provide software to interface the host processor
16 to the FPGA. The user enters user code 107 describing the
17 user interface instructions, which is then compiled using
18 compiler 108 to produce executable code 109. The
19 instructions in executable code 109 are then used by the
20 processor to communicate with the configured FPGA 106. It
21 is also known to use executable code 109 to control the
22 configuration of FPGA 106 with bitstream file 105. This
23 series of tasks is usually completely decoupled from the
24 task of designing the circuit and hence can be difficult and
25 error-prone.

26 In addition to the problems of interfacing the hardware
27 and software in this environment, there is also the problem
28 of design cycle time. Any change to the circuit design
29 requires a complete pass through the hardware design tool
30 chain (101-106 in Figure 1). This process is time
31 consuming, with the place and route portion of the chain
32 typically taking several hours to complete.

33 Finally, this approach provides no support for
34 reconfiguration. The traditional hardware design tools
35 provide support almost exclusively for static design. It is
36 difficult to imagine constructs to support run-time

1 reconfiguration in environments based on schematic or HDL
2 design entry.

3 In contrast, the MDRC environment comprises a library
4 of elements which permit logic and routing to be specified
5 and configured in a reconfigurable logic device. By making
6 calls to these library elements, circuits may be configured
7 and reconfigured. Additionally, host code may be written to
8 interact with the reconfigurable hardware. This permits all
9 design data to reside in a single system, often in a single
10 Java source code file.

11 In addition to greatly simplifying the design flow, as
12 shown in Figure 2, the MDRC approach also tightly couples
13 the hardware and software design processes. Design
14 parameters for both the reconfigurable hardware and the host
15 software are shared. This coupling provides better support
16 for the task of interfacing the logic circuits to the
17 software.

18 As shown in Figure 2, entering and compiling an FPGA
19 circuit using the MDRC method requires many fewer steps than
20 in the prior art method of Figure 1. User code 201, in this
21 embodiment Java code, is entered. This code includes not
22 just instructions describing the user interface and the
23 configuration process, but also a high-level description of
24 the desired FPGA circuit. This circuit description
25 comprises calls to library elements (function calls) in MDRC
26 libraries 202. In one embodiment, these cells can be
27 parameterized. Java compiler 203 combines the circuit
28 descriptions from MDRC libraries 202 with the instructions
29 from user code 201 to generate executable code 204.
30 Executable code 204 includes not only user interface
31 instructions, as in executable code 109 of Figure 1, but
32 also configuration instructions. When using MDRC, the
33 bitstream need not be stored as a file; if desired the
34 configuration data can be directly downloaded to FPGA 106 by
35 executable code 204. This technique is particularly useful
36 in reconfigurable computing, i.e., when using a

1 reconfigurable FPGA as a coprocessor to perform a series of
2 different computations for a microprocessor.

3
4 The MDRC Abstraction

5 MDRC takes a layered approach to representing the
6 reconfigurable logic. At the lowest (most detailed) layer,
7 called Level 0, MDRC supports all accessible hardware
8 resources in the reconfigurable logic. Extensive use of
9 constants and other symbolic data makes Level 0 usable, in
10 spite of the necessarily low level of abstraction.

11 The current platform for the MDRC environment is the
12 XC6200DS Development System manufactured by Xilinx, Inc. the
13 assignee of the present invention. The XC6200DS Development
14 System comprises a PCI board containing a Xilinx XC6216
15 FPGA. In the XC6200 family of FPGAs, Level 0 support
16 comprises abstractions for the reconfigurable logic cells
17 and all routing switches, including the clock routing. The
18 code for Level 0 is essentially the bit-level information in
19 the XC6200 Data Sheet coded into Java. (The "XC6200 Data
20 Sheet" as referenced herein comprises pages 4-251 to 4-286
21 of the Xilinx 1996 Data Book entitled "The Programmable
22 Logic Data Book", published September 1996, available from
23 Xilinx, Inc., 2100 Logic Drive, San Jose, California 95124.
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25 copying these and other pages referenced herein but
26 otherwise reserves all copyright rights whatsoever.)

27 While Level 0 provides complete support for configuring
28 all aspects of the device, it is very low level and may be
29 too tedious and require too much specialized knowledge of
30 the architecture for most users. Although this layer is
31 always available to the programmer, it is expected that
32 Level 0 support will function primarily as the basis for the
33 higher layers of abstraction. In this sense, Level 0 is the
34 "assembly language" of the MDRC system.

35 Above the Level 0 abstraction is the Level 1
36 abstraction. This level of abstraction permits simpler

1 access to logic definition, clock and clear routing, and the
2 host interface.

3 The most significant portion of the Level 1 abstraction
4 is the logic cell definition. Using the logic cell
5 definition, one logic cell in the XC6200 device can be
6 configured as a standard logic operator. In one embodiment,
7 AND, NAND, OR, NOR, XOR, XNOR, BUFFER and INVERTER
8 combinational logic elements are supported. These elements
9 may take an optional registered output. Additionally, a D
10 flip-flop and a register logic cell are defined. In one
11 embodiment, a latch cell is defined instead of or in
12 addition to the flip-flop element. All of these logic
13 operators are defined exclusively using MDRC level 0
14 operations, and hence are easily extended.

15 Figure 3 is a diagram of the Level 1 logic cell
16 abstraction. Outputs Nout, Eout, Sout, Wout correspond to
17 the outputs of the same names in the XC6200 logic cell, as
18 pictured on page 4-256 of the XC6200 data sheet. The XC6200
19 logic cell is also shown in Figure 3A herein. Input Sin of
20 Figure 3 corresponds to input S of the logic cell of Figure
21 3A, input Win corresponds to input W, Nin to N, and Ein to
22 E. The Level 1 abstraction shown in Figure 3 is a
23 simplified representation of the XC6200 logic block. In
24 this embodiment, for example, inputs S4, W4, N4, and E4 are
25 not supported in the Level 1 abstraction, although they are
26 supported in the Level 0 abstraction. The Logic block and
27 flip-flop shown in Figure 3 signify the circuits available
28 in one XC6200 logic cell. Inputs A, B, and SEL in Figure 3
29 (corresponding to inputs X1, X2, and X3 of Figure 3A) are
30 the inputs to the Logic block; they can be mapped to any of
31 logic cell inputs Sin, Win, Nin, and Ein. The circuits
32 available in one logic cell differ in other FPGA devices.

33 In addition to the logic cell abstraction, the clock
34 routing is abstracted. Various global and local clock
35 signals (such as Clk and Clr in Figure 3) may be defined and
36 associated with a given logic cell.

1 A third portion of the MDRC Level 1 abstraction is the
2 register interface. In the XC6200 device, columns of cells
3 may be read or written via the bus interface, the columns of
4 cells thus forming read/write registers. The Register
5 interface allows registers to be constructed and accessed
6 symbolically.

7 8 An Example

9 Figure 4 shows a simple counter designed for an XC6200
10 device, based on toggle flip-flops 402 and carry logic 401
11 using the Level 1 abstraction. In less than 30 lines of
12 code, the circuit is described and configured, and clocking
13 and reading of the counter value is performed. In addition,
14 the structure of this circuit permits it to be easily
15 packaged as a parameterized object, with the number of bits
16 in the counter being set via a user-defined parameter. Such
17 an object-based approach would permit counters of any size
18 to be specified and placed at any location in the XC6200
19 device. Once implemented, the counter of Figure 4 could
20 also be placed in a library of parameterized macrocells.

21 The implementation process is fairly simple. First,
22 the logic elements required by the circuit are defined.
23 These circuit element definitions are abstractions and are
24 not associated with any particular hardware implementation.

25 Once these logic elements are defined, they may be
26 written to the hardware, configuring the circuit. Once the
27 circuit is configured, run time interfacing of the circuit,
28 usually in the form of reading and writing registers and
29 clocking the circuit, is performed. If the application
30 demands it, the process may be repeated, with the hardware
31 being reconfigured as necessary.

32 The counter example contains nine basic elements. Five
33 basic elements provide all necessary support circuitry to
34 read, write, clock and clear the hardware. The remaining
35 basic elements are used to define the counter circuit
36 itself. These elements are best seen by looking at Figure 5
37 in conjunction with Figure 4. Figure 5 gives the MDRC code

1 for describing the basic elements. The pci6200 object
2 passed to each of the two register definitions is the
3 hardware interface to the XC6200DS PCI board.

4 The support circuitry includes two registers which
5 simply interface the circuit to the host software. These
6 two registers are used to read the value of the counter
7 ("Register counterReg" in Figure 5) and to toggle a single
8 flip-flop 404, producing the local clock ("Register
9 clockReg" in Figure 5). To support the flip-flops in the
10 XC6200 device, clock and clear (reset) inputs must also be
11 defined. The global clock ("ClockMux globalClock" in Figure
12 5) is the system clock for the device and must be used as
13 the clock input to any writable register. In this circuit,
14 the flip-flop which provides the software-controlled local
15 clock must use the global clock. The local clock ("ClockMux
16 localClock" in Figure 5) is the output of the software
17 controlled clock, and must be routed to the toggle flip-
18 flops which make up the counter. Finally, all flip-flops in
19 the XC6200 device need a clear input ("ClearMux clear" in
20 Figure 5). In this embodiment, the clear input to all flip-
21 flops is simply set to logic zero (GND).

22 The first logic element in the counter circuit is the
23 clock ("Logic clock" in Figure 5). This element is just a
24 single bit register 404 (Figure 4) which is writable by the
25 software. Toggling register 404 via software control
26 produces clock Local_clock for the counter circuit. The
27 next counter circuit element is a toggle flip-flop such as
28 flip-flop 402, ("Logic tff" in Figure 5). This flip-flop is
29 defined as having an input coming from the west. (According
30 to the standard XC6200 data sheet nomenclature, the names
31 Logic.EAST and Ein denote an east-bound signal, i.e., a
32 signal coming from the west.) The toggle flip-flop element
33 provides the state storage for the counter. Next, the carry
34 logic element 401 for the counter ("Logic carry" in Figure
35 5) is simply an AND-gate with inputs from the previous stage
36 carry logic and the output of the current stage toggle flip-
37 flop. The carry element generates the "toggle" signal for

1 the next stage of the counter. Figures 6A and 6B are
2 graphical representations of the flip-flop and carry logic
3 cells, respectively, in an XC6200 device. Finally, a
4 logical "one" or VCC cell ("Logic one" in Figure 5, block
5 403 in Figure 4) is implemented for the carry input to the
6 first stage of the counter.

7 Once this collection of abstract elements is defined,
8 they may be instantiated anywhere in the XC6200 cell array.
9 This instantiation is accomplished by making a call to the
10 write() function associated with each object. This function
11 takes a column and row parameter which define the cell in
12 the XC6200 device to be configured. Additionally, the
13 hardware interface object is passed as a parameter. In this
14 case, all configuration is done to pci6200, a single
15 XC6200DS PCI board.

16 An example of this instantiation is shown in Figure 7,
17 which instantiates the elements for the counter of Figure 4.
18 The code in Figure 7 performs all necessary configuration.
19 In the for() loop, the carry cells (401 in Figure 4) are in
20 one column with the toggle flip-flops tff (402 in Figure 4)
21 in the next column. A local clock and a clear are attached
22 to each toggle flip-flop tff. The relative location of
23 these cells is shown in Figure 4.

24 Below the for() loop, a constant "1" is set as the
25 input to the carry chain (403 in Figure 4). Next, the
26 software-controlled clock (Local_clock in Figure 4) is
27 configured. This is the clock object, with its localClock
28 routing attached to the toggle flip-flops tff of the
29 counter. Finally, the global clock is used to clock the
30 software-controlled local clock. In some embodiments, the
31 clock and clear basic elements are not required; in this
32 embodiment their presence is necessary to support the XC6200
33 architecture.

34 Once the circuit is configured, it is a simple matter
35 to read and write the Register objects via the get() and
36 set() functions, respectively. In Figure 8A, the clock is
37 toggled by alternately writing "0" and "1" to the clock

1 register (404 in Figure 4). The counter register (not
2 shown) is used to read the value of the counter (outputs
3 COUNT[0], COUNT[1], COUNT [2], etc.). Figure 8B shows an
4 actual trace of the execution of this code running on the
5 XC6200DS development system.

6 7 Conclusions

8 While this example is a simple one for demonstration
9 purposes, it makes use of all the features of MDRC. These
10 features include register reads and writes, as well as
11 features such as software-driven local clocking. Other more
12 complex circuits have also been developed using MDRC. More
13 complex circuits are built using the same basic features;
14 the primary difference is in the size of the code.

15 MDRC provides a simple, fast, integrated tool for
16 reconfigurable logic based processing. MDRC is currently a
17 manual tool, since it is desirable for the programmer to
18 exercise tight control over the placement and routing of
19 circuits for reconfigurable computing. However, MDRC
20 provides very fast compilation times in exchange for the
21 manual design style. The compile times necessary to produce
22 these circuits and run-time support code is on the order of
23 seconds, many orders of magnitude faster than the design
24 cycle time of traditional CAD tools. This unusual speed
25 permits development in an environment that is similar to a
26 modern integrated software development environment.
27 Additionally, the object-oriented nature of Java permits
28 libraries of parameterized cells to be built. This feature
29 could significantly increase the productivity of MDRC users.

30 MDRC may be used as a basis for a traditional graphical
31 CAD tool. This approach would be useful for producing
32 static circuits.

33 The above text describes the MDRC in the context of
34 FPGAs used for dynamically reconfigurable computing, such as
35 the Xilinx XC6200 family of FPGAs. However, the invention
36 can also be applied to other FPGAs and other software
37 programmable ICs not used for dynamically reconfigurable

1 computing.

2 Those having skill in the relevant arts of the
3 invention will now perceive various modifications and
4 additions which may be made as a result of the disclosure
5 herein. Accordingly, all such modifications and additions
6 are deemed to be within the scope of the invention, which is
7 to be limited only by the appended claims and their
8 equivalents.

9

1 CLAIMS

2 What is claimed is:

3

4 1. A method of configuring a field programmable gate array
5 (FPGA), the FPGA being connected to a host processor for
6 configuration thereby; the method comprising the steps of:

7 a) programming the host processor with instructions in
8 a high level programming language;

9 b) instantiating elements from a library of elements
10 compatible with the high level programming language;

11 c) providing a compiler to the host processor for
12 generating executable code in response to the programmed
13 instructions and the instantiated library elements; and

14 d) configuring the FPGA from the host processor in
15 response to the executable code.

16

17 2. The method recited in Claim 1 wherein the FPGA is used
18 for dynamically reconfigurable computing.

19

20 3. The method recited in Claim 1 or Claim 2 wherein the
21 high level language is Java.

22

23 4. The method recited in Claim 1 or Claim 2 wherein the
24 library comprises combinational logic elements.

25

26 5. The method recited in Claim 1 or Claim 2 wherein the
27 library comprises flip-flop elements.

28

29 6. The method recited in Claim 1 or Claim 2 wherein the
30 library comprises latch elements.

31

32 7. The method recited in Claim 1 or Claim 2 further
33 comprising the step of:

34 e) using the library elements to generate a
35 parameterized cell.

36

37

- 1 8. The method recited in Claim 7 wherein the cell is a
2 counter parameterized by the number of bits in the counter.
3
- 4 9. A method of configuring a field programmable gate array
5 (FPGA) for dynamically reconfigurable computing; the method
6 comprising the steps of:
7 a) programming the host processor with instructions in
8 a high level language;
9 b) providing a compiler running on the host processor
10 for generating executable code in response to the
11 instructions; and
12 c) connecting the host processor to the FPGA for
13 dynamic reconfiguration programming of the FPGA by the host
14 processor via the executable code.
15
- 16 10. The method recited in Claim 9 wherein the high level
17 language is Java.
18
- 19 11. The method recited in Claim 9 further comprising the
20 step of:
21 d) instantiating elements from a library of elements
22 compatible with the compiler.
23
- 24 12. The method recited in Claim 11 wherein the library
25 comprises combinational logic elements.
26
- 27 13. The method recited in Claim 11 wherein the library
28 comprises flip-flop elements.
29
- 30 14. The method recited in Claim 11 wherein the library
31 comprises latch elements.
32
33
34
35
36
37

1/7

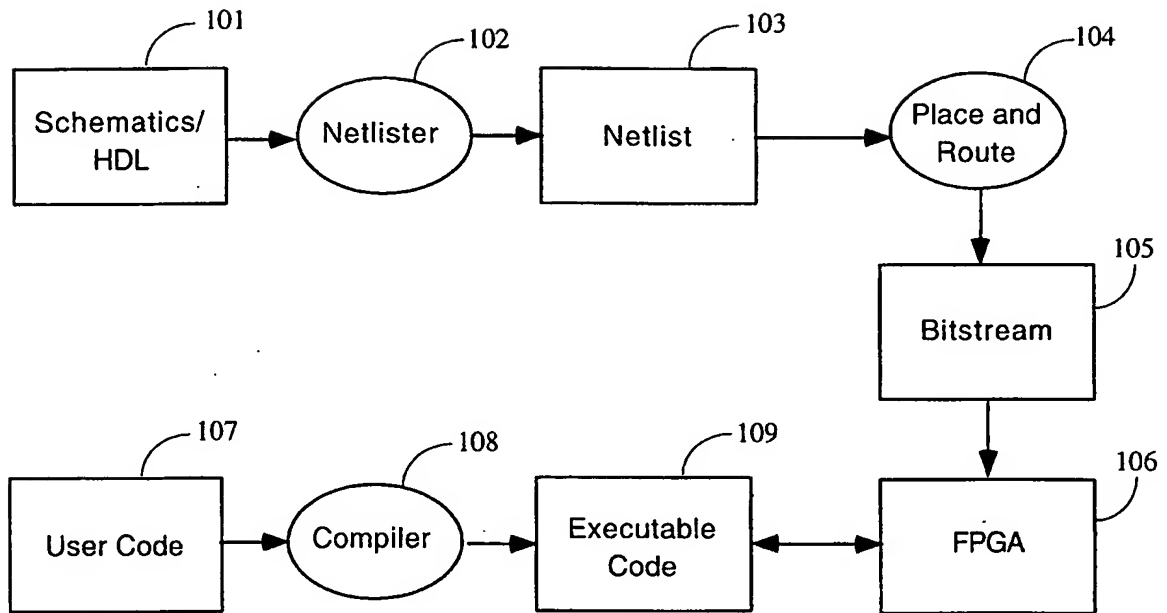


FIG. 1 (Prior Art)

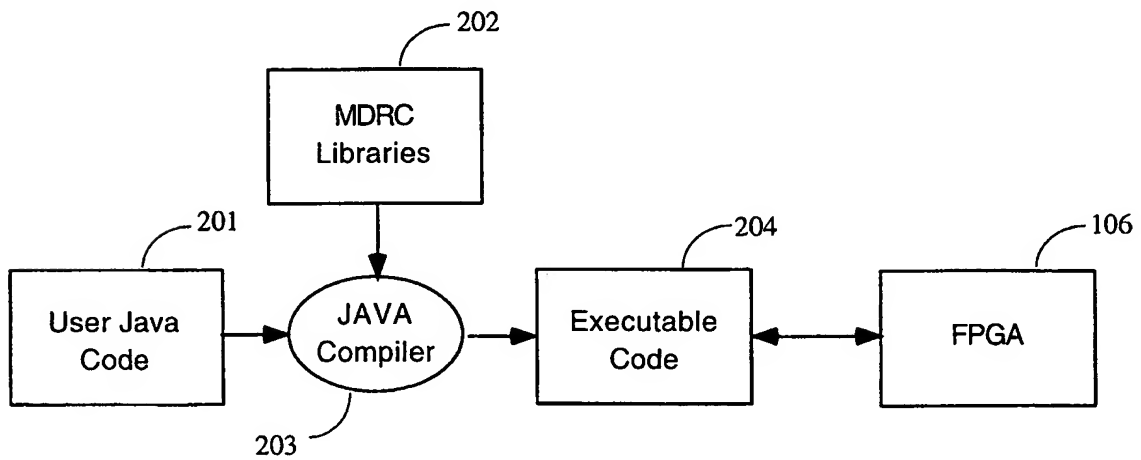


FIG. 2

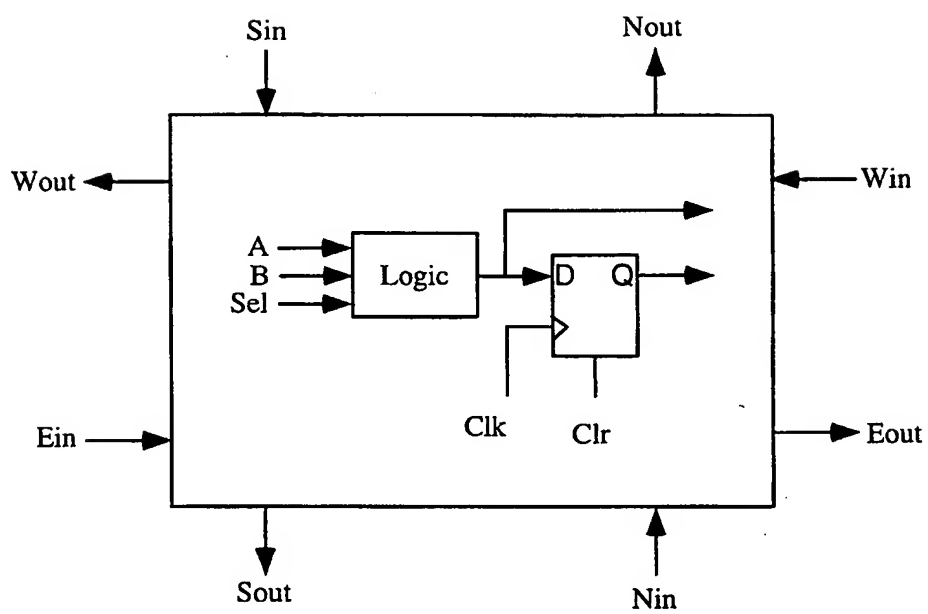


FIG. 3

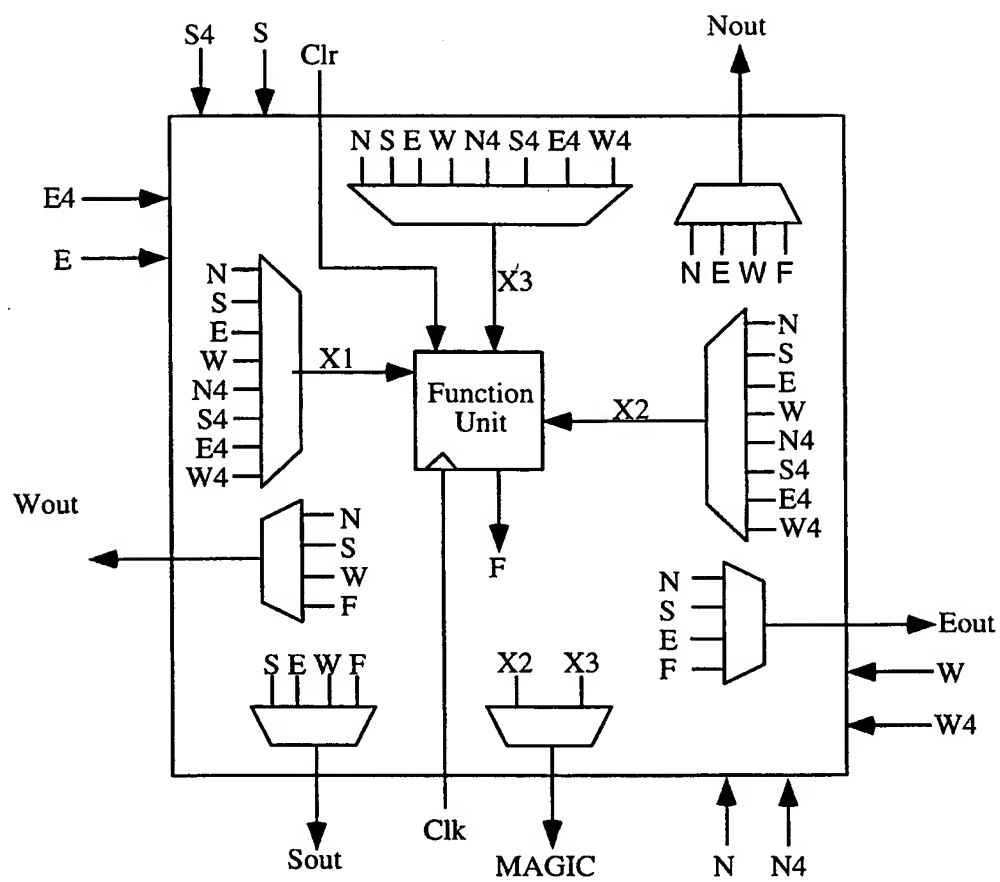


FIG. 3A
(Prior Art)

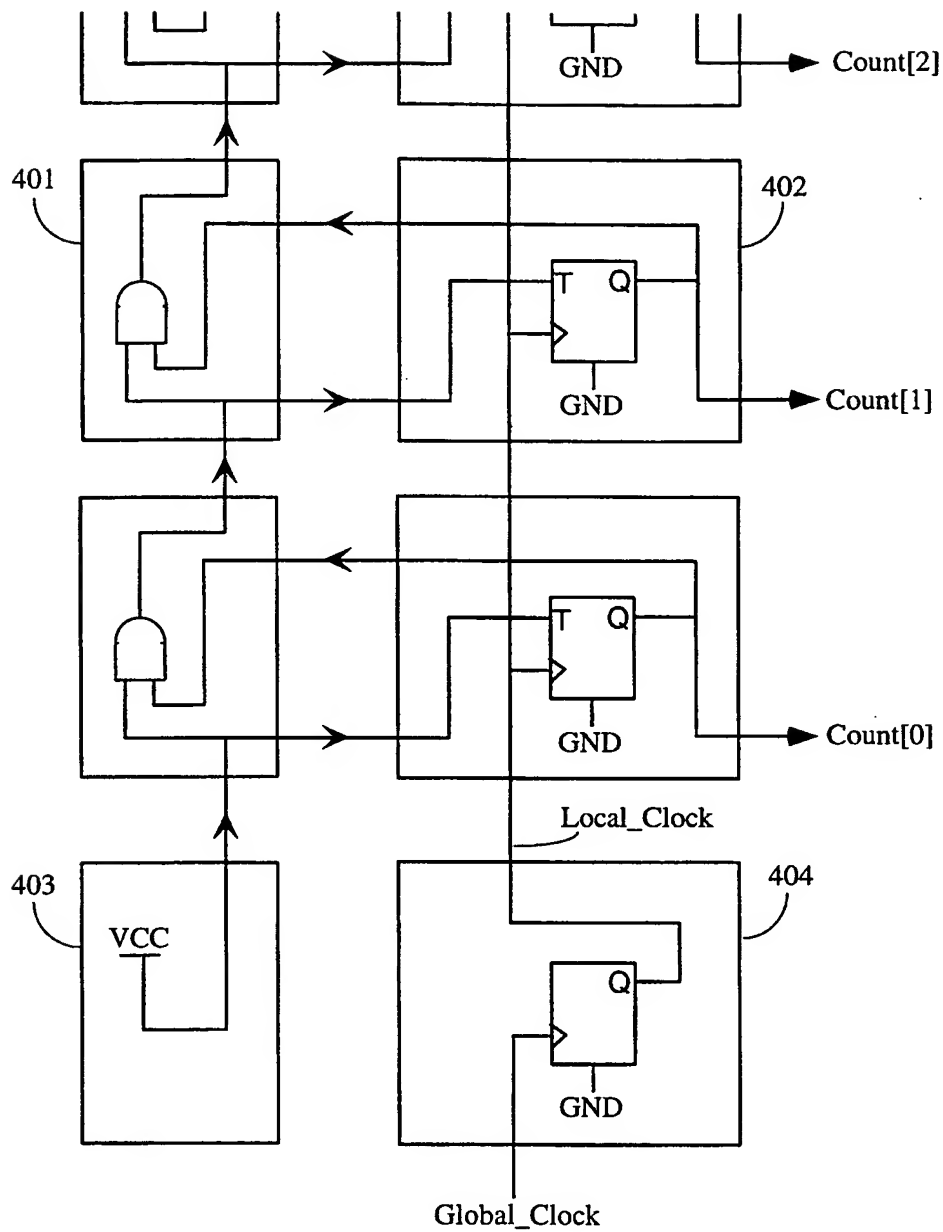


FIG. 4

```
Pci6200 pci6200 = new Pci6200N(null); // Hardware interface
pci6200.connect();
Register counterReg =      new Register(COLUMN, counterMap, pci6200);
Register clockReg =        new Register(COLUMN, clockMap, pci6200);
ClockMux localClock =      new ClockMux(ClockMux.CLOCK_IN);
ClockMux globalClock =     new ClockMux(ClockMux.GLOBAL_CLOCK);
ClearMux clear =           new ClearMux(ClearMux.ZERO);
Logic tff =                new Logic(Logic.T_FLIP_FLOP, Logic.EAST);
Logic clock =              new Logic(Logic.REGISTER);
Logic one =                new Logic(Logic.ONE);
Logic carry =              new Logic(Logic.AND, Logic.NORTH, logic.WEST);
carry.setEastOutput(Logic.NORTH); // Set carry output
```

FIG. 5

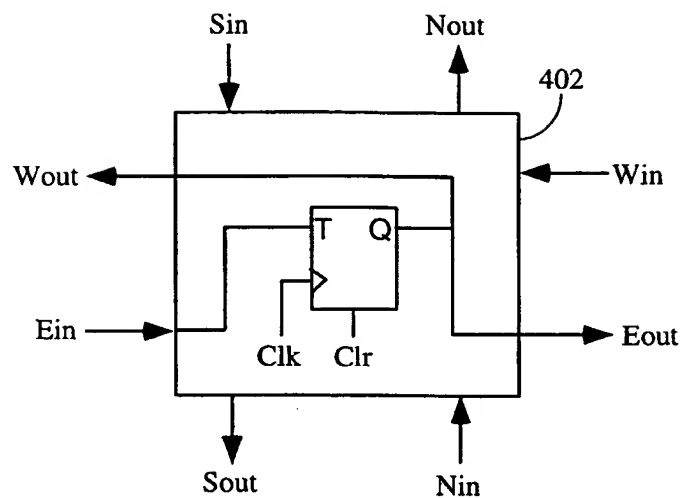


FIG. 6A

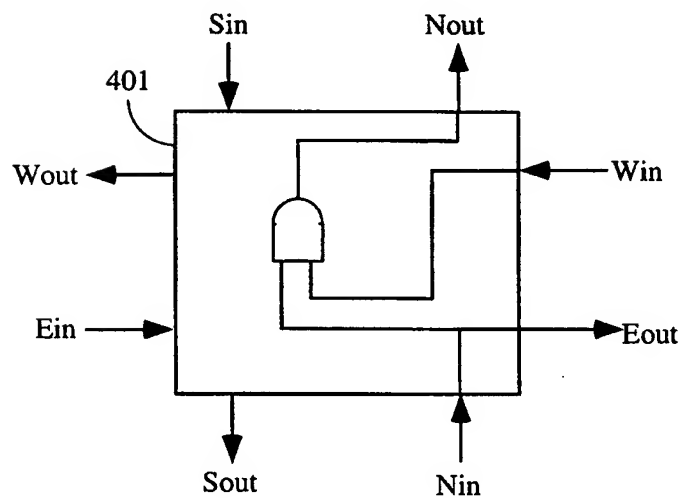


FIG. 6B


```
/* Configure cells */
for (i=ROW_START; i<ROW_END; i++) { // The counter
    carry.write((COLUMN-1), i, pci6200);
    tff.write(COLUMN, i, pci6200);
    localClock.write(COLUMN, i, pci6200);
    clear.write(COLUMN, i, pci6200);
} /* end for */
one.write((COLUMN-1), (ROW_START-1), pci6200); // Carry in
clock.write(COLUMN, (ROW_START-1), pci6200); // Clock
localClock.set(ClockMux.NORTH_OUT);
localClock.write(COLUMN, ROW_START, pci6200);
globalClock.write(COLUMN, (ROW_START-1), pci6200);
```

FIG. 7

```
for (i=0; i<5; i++) {
    clockReg.set(0); // Toggle clock
    clockReg.set(1);
    System.out.println("Count: " + counterReg.get());
} /*end for() */
```

FIG. 8A

```
C: \java\JERC> java Counter
Count: 0
Count: 1
Count: 2
Count: 3
Count: 4
C: \java\JERC>
```

FIG. 8B

INTERNATIONAL SEARCH REPORT

Intr onal Application No
PCT/US 98/16436

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G06F17/50

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category * | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|------------|--|-----------------------|
| X | WO 94 10627 A (GIGA OPERATIONS CORP ; TAYLOR BRAD (US); DOWLING ROBERT (US)) 11 May 1994 see page 8, line 5 - line 11 see page 35, line 6 - page 43, line 2 see page 45, line 1 - line 8; figures 17-30 --- | 1-14 |
| A | US 5 499 192 A (KNAPP STEVEN K ET AL) 12 March 1996 see column 3, line 53 - column 4, line 37 --- | 1-14 |
| A | EP 0 645 723 A (AT & T CORP) 29 March 1995 see page 3, line 29 - line 39 see page 4, line 9 - line 13 --- | 1-14 |
| | -/-- | |

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

8 December 1998

Date of mailing of the international search report

28/12/1998

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| C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT | | |
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| Category ² | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
| P,X | <p>LECHNER E ET AL: "The Java Environment for Reconfigurable Computing" FIELD-PROGRAMMABLE LOGIC AND APPLICATIONS. 7TH INTERNATIONAL WORKSHOP, FPL '97. PROCEEDINGS, FIELD-PROGRAMMABLE LOGIC AND APPLICATIONS. 7TH INTERNATIONAL WORKSHOP, FPL '97. PROCEEDINGS, LONDON, UK, 1-3 SEPT. 1997, pages 284-293, XP002086682 ISBN 3-540-63465-7, 1997, Berlin, Germany, Springer-Verlag, Germany see the whole document -----</p> | 1-14 |

INTERNATIONAL SEARCH REPORT

information on patent family members

Int'l Application No

PCT/US 98/16436

| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
|---|---------------------|----------------------------|---------------------|
| WO 9410627 A | 11-05-1994 | US 5535342 A | 09-07-1996 |
| | | AU 5458194 A | 24-05-1994 |
| | | CA 2148813 A | 11-05-1994 |
| | | EP 0746812 A | 11-12-1996 |
| | | JP 8504285 T | 07-05-1996 |
| | | AU 5593594 A | 24-05-1994 |
| | | CA 2148814 A | 11-05-1994 |
| | | EP 0667010 A | 16-08-1995 |
| | | JP 8504514 T | 14-05-1996 |
| | | WO 9410624 A | 11-05-1994 |
| | | US 5497498 A | 05-03-1996 |
| | | US 5603043 A | 11-02-1997 |
| US 5499192 A | 12-03-1996 | NONE | |
| EP 0645723 A | 29-03-1995 | CA 2126265 A | 28-03-1995 |
| | | JP 7152806 A | 16-06-1995 |
| | | US 5594657 A | 14-01-1997 |